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The Investigation And Development Of Ground Waters.

THE INVESTIGATION AND DEVELOPMENT OF GROUND WATERS

BY

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B. S., MUNICIPAL AND SANITARY ENGINEERING

UNIVERSITY OF ILLINOIS, 1911

THESIS

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE

DEGREE OF
CIVIL ENGINEER

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1916

UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

April 13, 1916. 191

I HEREBY RECOMMEND THAT THE THESIS PREPARED BY

ARTHUR LUDWIG ENGER

ENTITLED The Investigation and Development of Ground Waters

BE ACCEPTED AS FULFILLING THIS PART ON THE REQUIREMENTS FOR THE

PROFESSIONAL DEGREE OF CIVIL ENGINEER

A. N. Talbot

Head of Department of Municipal and Sanitary Engineering.

Recommendation concurred in:

Ira O. Baker.
F. H. Newell
A. N. Talbot

Committee

Frontispiece– Pumping test of drilled well; 1850 gallons per minute.

TABLE OF CONTENTS

LIST OF PLATES

THE INVESTIGATION AND DEVELOPMENT OF GROUND WATERS

I. INTRODUCTION

Because of the small quantity of ground water available and the expense of developing groundwater supplies, compared with surface water supplies, and because of the difficulty of studying the movements of water under the ground surface and out of sight, the branch of hydrology relating to ground waters has lagged far behind the science of stream flow. For municipal or domestic purposes, well waters may be more desirable than surface waters because of the better sanitary quality of the former. Ground waters are developed for irrigation only when the surface water supplies are inadequate. However, the importance of groundwater supplies has increased with the improvements of pumping machinery, and with improvements in well sinking methods. Also, the "back-to-the-land" movement of the last decade has created a demand for irrigated lands, and this naturally has led to increased interest in pump irrigation.

While groundwater supplies are small compared with surface water supplies, the greater expense of the works for utilizing the ground waters demands that careful investigations of the underflow be made before development

is begun. The result of over-development of the underground supply, too, is more serious than with surface supplies.

The writer's experience with ground waters has been principally in Arizona, and because of this, although an attempt has been made to present a general discussion of the subject, the following will naturally apply particularly to that region, where broad, uniformly sloping arid valleys lie between the ranges of mountains. Precipitation occurs in two well defined seasons, winter and summer. Rainfall increases rapidly with altitude, hence the large streams have their sources in the higher mountain ranges. Most of the runoff is as flood flow; perennial streams are uncommon. The valley fill generally contains much coarse, porous material, and wells yielding several cubic feet of water per second, with a moderate drawdown, are often obtained. Indeed, as the principal use of ground water is for irrigation, wells yielding less than a second-foot are considered as unsatisfactory.

The writer wishes to acknowledge his indebtedness to Prof. George E. P. Smith, Irrigation Engineer of the Arizona Agricultural Experiment Station, under whose direction the writer has carried on his groundwater studies. A list of the publications referred to in the writing of this thesis is given in the bibliography at the close of this paper, and, in lieu of more specific reference in the text, acknowledgment is here made of the writer's debt to them.

II. GENERAL PRINCIPLES

The soils and rocks forming the top crust of the earth are porous to a greater or less degree, varying between wide limits. The porosity of some common materials in their natural state is approximately as follows:

Kind of material	Percentage of voids
Clay loam	35 to 50
Sand	25 to 40
Sand rock	5 to 30
Limestone	1 to 15
Granite	0.25 to 1

The size of the pore spaces also varies greatly, the spaces in fine grained materials, such as clay, being very small, while in coarse materials such as sand and gravel the pore spaces may be large. If the material is composed of a mixture of many sized grains, the size of the pore spaces will be largely controlled by the finer material which fills the spaces between the larger grains.

Under natural conditions the pore spaces are either partially or completely filled with water, depending on whether the material lies above or below the groundwater table or plane of saturation.

The waters in the soil may be divided into three classes according to their manner of occurrence and movement; hygroscopic moisture, capillary moisture,

and gravity water.

Hygroscopic moisture is that which an absolutely dry soil will absorb when exposed to a moist atmosphere. A natural soil, even when apparently dry, always contains some hygroscopic moisture. The amount of water that an absolutely dry soil will absorb from a saturated atmosphere depends mainly upon the temperature and the type of soil. Prof. Loughbridge has found that California soils will absorb the following amounts of hygroscopic moisture.

Kind of soil	Hygroscopic moisture in percent of dry weight of soil
Sandy soils	1 to 3
Sandy loam soils	3 to 5
Loam soils	5
Clay loam soils	5 to 7
Clay soils	7 to 10

Hygroscopic moisture exists as very thin films of water surrounding the soil particles, but differs from capillary water in that there is no movement from one part of the soil to another. Plants can use but very little hygroscopic moisture.

Capillary water is held in the small pore spaces and as thickened films around the soil particles by surface tension. As some portion of the soil becomes drier, the films of water around those soil particles become thinner, exert a greater force, and consequently draw some water

from the adjoining particles of soil; this action continued causes the slow movement of water from one part of the soil to another. If it were not for the influence of gravity the tendency would be for the films to become of equal thickness throughout the soil mass. Capillary movements are very slow, particularly in soils far removed from a supply of free water. The limit to which water may be raised by capillarity depends upon the character of the soil mainly. It is commonly stated that in coarse, sandy soil, gravity water will be drawn to the surface through the capillary spaces from depths not exceeding four feet, and in a fine sandy or clayey soil, water will be drawn from depths as great as eight feet. The quantity of capillary water which a soil may hold depends on the character of the soil. Fine soils have a greater surface for the thin films of water to cover and more capillary spaces, and will therefore retain more capillary water. Plants depend for their water supply wholly upon capillary water.

As a soil becomes more and more nearly saturated, a point is reached where gravity exerts a stronger pull than surface tension, and the water begins to move under the influence of gravity. This point is reached when the soil is nearly saturated. Unless there is a continuous downward movement of water from the ground surface, there will be no gravity water above the water table. The groundwaters which are available for water supplies are gravity waters.

According to their source, ground waters may be

divided into three classes:

Magmatic waters, or waters resulting from the chemical changes attendant upon the formation of rocks.

Connate waters, or waters trapped in the sedimentary rocks during their formation.

Meteoric waters, or waters derived from rainfall.

Only the latter class is of importance in connection with water supplies. Some mineral waters are magmatic waters, but, of course, the supply of both magmatic and connate waters is limited, and is not being replenished.

Rainfall is disposed of in a variety of ways. Part is caught on the leaves of plants or remains on the ground surface in pools, and is returned to the atmosphere immediately after the storm, by evaporation. Part runs off on the surface. Part percolates downward, to be returned to the atmosphere by transpiration or evaporation, or to be returned to the ground surface as stream flow, or to percolate through the underground to the sea.

The rainfall that is intercepted by vegetation or that is evaporated directly from the ground surface after a rain is a large percentage of the precipitation in light showers, but is only a small part of heavy showers.

The part of the rain which is disposed of directly as runoff appears as flood flow. Where the groundwater table is below the drainage channels flood flows form the only runoff. Under ordinary soil conditions and light showers very little water runs off directly; but when the ground is frozen or is already saturated from previous rains, or if the soil is impervious, nearly the entire precipitation may be disposed of as flood flow. Sudden, heavy downpours of rain will also cause floods.

The water which percolates downward into the soil moves under the influence of both gravity and of capillary forces. The water moves downward until the surface of the saturated zone is reached, and then moves along with the underflow in accordance with the laws of gravity, unless at some point in its downward movement the quantity of water in the soil is so small that capillary forces can hold the water against gravity.
In the arid regions of the Southwest, where the average annual rainfall is small and the water table is more than twenty feet below the surface, the distribution of soil moisture is normally as follows:

Top foot - Hygroscopic moisture only, except immediately after rains.

Second to sixth foot - Some capillary moisture for a considerable time after rains.

Below six feet and more than ten feet above the water table - Hygroscopic moisture.

Less than ten feet above the water table - Capillary water, the quantity varying with the distance above the water table.

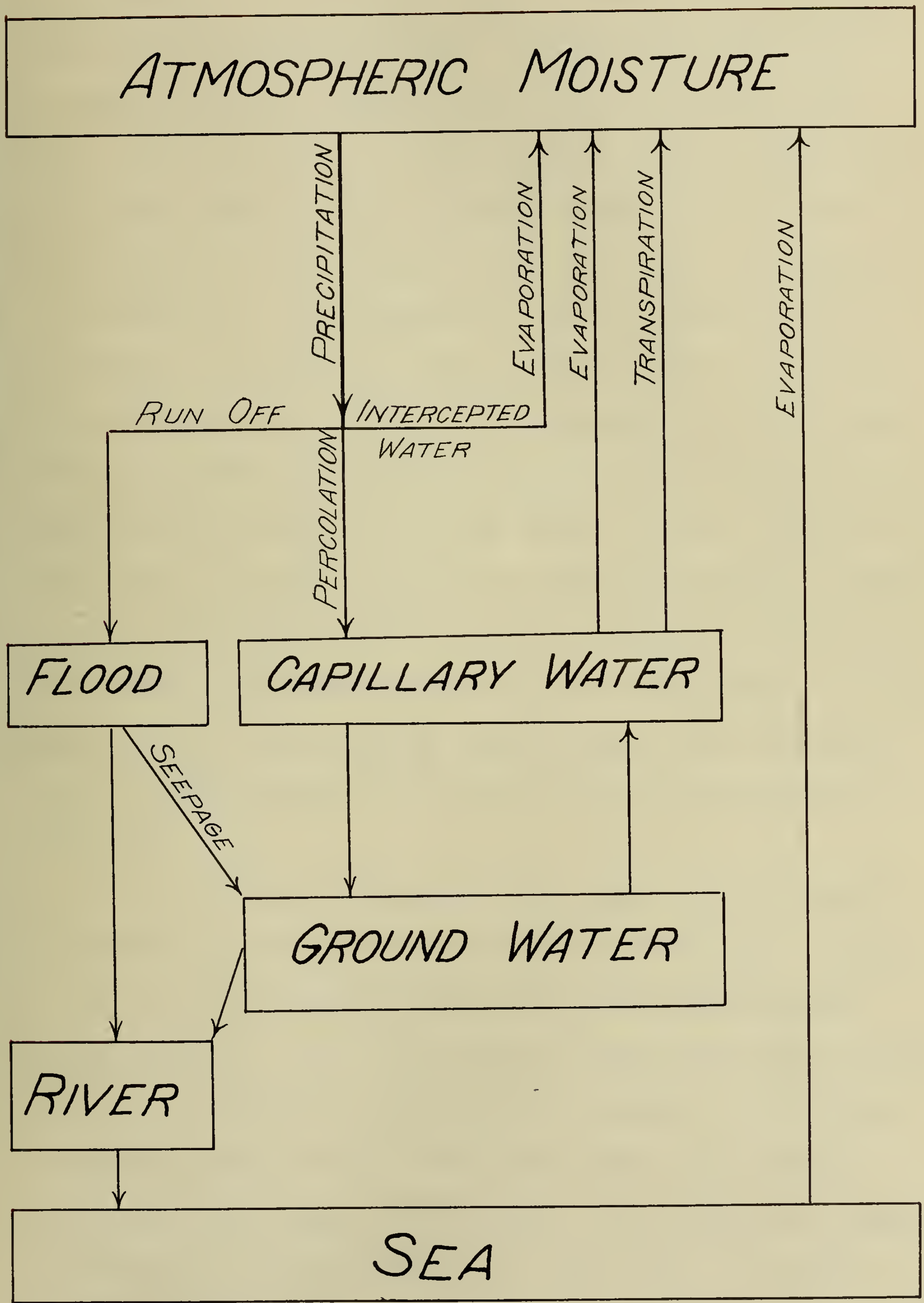
The zone of comparatively dry soil more than ten feet above the water table has a great capacity for holding capillary moisture, each foot of soil being able to retain an inch or more of water. All of this overlying soil must receive more water than it can hold as capillary water before any water can percolate downward to the water table. Should unusual conditions cause a large amount of water to percolate downward so as to moisten the dry soil, the moisture will remain in the ground only temporarily, being later removed by the roots of plants. The above will be true wherever the climate is such that the growth of plants is limited only by the amount of moisture available in the soil, such as is the case in the semi-arid regions. If the water table is but a short distance from the ground surface, the soil will normally hold all the water that can be held by capillarity against gravity, and any additional amount that is added from rainfall will flow downward and unite with the ground water. In a humid climate, where the growth of vegetation is limited by light and heat, and not by moisture, the soil, even at considerable distances above the water table will normally have nearly all the capillary water that it can hold, and precipitation on the surface will quickly establish connection with the water table.

An attempt has been made to represent graphically the disposal of rainfall in Plate I. It is realized that

the diagram is incomplete, but it is believed that the main features of the subject of hydrology are correctly outlined.

The groundwater table is the surface of the saturated zone or the surface to which water will rise in wells tapping the uppermost stratum of water bearing material. The groundwater table usually conforms somewhat to the surface of the overlying ground, but is generally more uniform and the slopes are less. Where streams are fed by ground water the slope of the water table is toward the stream. If the streams are above the water table, the slope of the water table is generally parallel to the slope of the overlying stream bed, unless there is considerable seepage from the stream bed, in which case the slope of the water table will be downstream and away from the stream.

In the arid southwestern valleys where the surface drainage is toward a central playa or "alkali flat", the slopes of the water table are generally flatter than the surface slopes, the depths to water being much greater near the rim of the valley than in the center of the valley. There is one frequent exception to this rule where the mountains bordering the valley are high. There will often be a shallow water district near the mouth of large canyons, being a small area in which the water table is much higher than the normal water table of the valley.



Hydrologic Chart

The boundary of the alkali flat is usually about where the depth to the water table is eight feet, the depth to water under the alkali flat being less than eight feet. The alkali is a product of the evaporation of the ground water. There being no outlet for surface drainage all the precipitation in a closed basin must be returned to the atmosphere. The evaporation rate is so high, ordinarily, that the water table is kept below the ground surface. If the inflow is greater than evaporation from the ground surface under which the depth to water table is less than eight feet, the water table will rise until there is a sufficient surface exposed to evaporation to take care of the increased flow, and possibly a salt lake will appear in the center of the playa. If the underflow is less than the evaporation, the evaporation area will shrink until the underflow and evaporation are balanced.

The word "artesian" when used with reference to ground waters may be defined in several ways. Commonly the term "artesian" is applied only to water which rises in wells, due to its own pressure, above the ground surface. Technically, the term is applied to all waters which will rise in wells above the top of the porous strata in which they are contained. The principal conditions necessary for artesian water in a well are as follows: a porous stratum under an impervious stratum, with a place for inflow into the porous stratum at a higher elevation

than the top of the porous stratum at the well; the natural outlet of the water bearing stratum must be at an elevation higher than the top of the water bearing stratum at the well, or else the outlet must be so small or so distant that the hydraulic gradient will lie above the top of the porous stratum at the well.

III. LAWS OF FLOW OF WATER THROUGH SANDS

The rate of flow of water through sands depends upon the head of water causing the flow, the length of the sand column, the porosity of the sand, the size of the sand particles, and the temperature of the water. It has been generally assumed, following the work of Darcy, that the flow of water through a given sand column is proportional to the head. Prof. King found that there was a tendency for the rate of flow to increase somewhat faster than the head. Krober of Stuttgart as a result of laboratory experiments derived the following empirical formula for the flow through sands;

$$Q = 1728\,F\left(\frac{dh}{d + 900\,l}\right)^{\frac{8+d}{8+2d}}$$

Q is the quantity of discharge
F is the area of the sand column
l is the length of the sand column
h is the head causing the flow
d is the diameter of the sand grains in mm

According to this formula the flow varies very nearly as the head for small diameters of sand grains, but for the larger diameters the flow varies as some power of the head which is greater than one. Because of the many uncertainties entering into any specific problem, for practical purposes it may be assumed that the rate of flow varies directly as the first power of the head. Lengthening the sand column is equivalent to reducing the head for a given length, hence pressure head and length of sand column are often combined into one factor called slope.

The rate of flow through a sand column varies rapidly with changes in porosity. An increase in porosity increases the area through which flow takes place, and also increases the size of the pore spaces, decreasing friction. The greater the size of the sand particles the greater the pore spaces will be, though the porosity or percentage of pore space may be low. As the finer particles fill in the spaces between the larger particles, the size of the pores will be influenced more by the finer particles of sand than by the larger.

Increasing the temperature of water decreases its viscosity, and thus increases the rate of flow through sand. The flow of water through sand is about doubled for a rise in temperature of fifty degrees Fahrenheit.

The formula most commonly used by American engineers is that of Allen Hazen which was derived from experiments on filter sand.

$$v = cd^2 \frac{h}{l}\left(\frac{t + 10°}{60}\right)$$

where v is the velocity of water in meters daily in a solid column of the same area as that of the sand
c is an approximately constant factor, varying from 500 to 1000 depending upon the character of the sand
d is the effective size of sand grain in millimeters
h is the loss of head
l is the thickness of sand through which the water passes
t is the temperature (Fahrenheit)

The effective size is considered to be that size of grain such that ten percent by weight of the particles are smaller and ninety percent larger than itself. It is assumed that

sands having the same effective size, other conditions being the same, will have the same rate of flow. Porosity is neglected in the formula and must be taken care of in the choice of the coefficient c. Hazen used the term "uniformity coefficient" to designate the ratio of the size of grain which has sixty percent of the sample finer than itself to the size which has ten percent finer than itself. Hazen says that the formula applies to filter sands with uniformity coefficients less than three, but also less closely to those with uniformity coefficients to six, and even ten. It does not apply to coarse gravels in which the viscosity of water is no longer controlling.

Charles S. Slichter derived the following formula from a theoretical investigation of the subject:

$$q = 0.2012\frac{pd^2s}{\mu h K}$$

q is the discharge in cubic feet per minute
p is the head under which the flow takes place
s is the area of the cross section of the sand column, in square feet
h is the length of the column
d is the mean diameter of the soil grains, or "so-called 'effective size'"
μ is the coefficient of viscosity, which varies with temperature
K is a constant which depends upon the porosity of the sand

Slichter's formula was published, together with tables computed from it, in several of the Water Supply Papers of the United States Geological Survey; hence it has been frequently used in groundwater investigations. It should be noted that

the mean diameter of sand grain, or effective size, used by Slichter is not the same as the effective size used in Hazen's formula. Slichter's mean diameter is found by means of an apparatus known as King's aspirator. In this method the effective size is determined by measuring the time required for the flow of a known amount of air through the sample, the measurements being made under a known pressure. As the screens necessary for determining the effective size as defined by Hazen are more often available to the engineer than an aspirator, the effective size is often determined from screen analysis and used with Slichter's formula, but this is no doubt a source of error. It is unfortunate that the same term was used for two different, though closely related, characteristics of sand.

Many difficulties arise in the application of the formulae to the flow of groundwater. The slope of the water table can be determined easily, but the area of cross section of the water bearing strata can be determined only approximately without great expense, and the determination of the porosity will be still more difficult. It will be necessary to assume a certain uniformity of conditions, an assumption that is rarely correct. Accurate estimates of the amount of underflow, therefore, cannot be obtained from the use of formulae. However, as with stream flow, formulae are valuable as indicating the general laws, and approximate values of the underflow may be obtained by their use, which may be accurate enough for many purposes.

IV. INVESTIGATION OF GROUND WATERS

While ground waters have been used since earliest times, it is only in recent years that sufficiently complete investigations have been carried on to permit the making of quantitative estimates of the amount of water which may be continuously drawn from an underground reservoir. The reason for the rarity of such studies is that it is unusual for a single organization or person to plan a comprehensive development of a groundwater supply. Ordinarily groundwater supplies have been developed gradually by individuals working independently, and none have felt it worth while to undertake a thorough study of the underground water. The investigations that were made were generally to find out where and how the largest quantity of water might be secured in one spot.

In recent years the growing needs of municipalities and the extensive development of irrigation by pumping have led to more complete investigations. Notable examples are the studies made by Charles H. Lee in Owens Valley, California for the Los Angeles Acqueduct Commission and by Walter E. Spear in Long Island for the Board of Water Supply, New York City. The United States Geological Survey has also made careful studies of many areas. As a result of this work the various steps of an investigation are now fairly well developed.

First of all, the limits of the district to be studied must be decided upon. In general, the investigation

must cover the entire area which may feed into the underground reservoir, or from which the losses from the underground reservoir may take place. Except in cases of artesian water, the limits of the district will probably be the same as for the surface drainage. For intensive study the district may be divided into smaller sections; sections which can be considered as representative of the entire district or large parts of the district, or else in some cases small areas may be selected in which all the recharge or losses takes place.

A reconnaissance should be made to collect information regarding the geology, general groundwater conditions, rainfall and surface runoff in order that the methods of studying the district may be outlined. The wells in the district should be located, as well as can be done easily, and depths to water measured. Bench marks should be established on well curbs so that all measurements of depth to water may be made from the same point. The custom of the Arizona Agricultural Experiment Station in marking bench marks on wooden curbs is to cut three notches, taking care to put the notches on timbers which will probably not be moved, and where the depth to water may easily be measured. On concrete curbs or drilled wells, the top of curb or casing at a described point is used as a bench mark. A chalked tape is used for making the measurement, with a weight on the end sufficiently heavy so that it is easy to feel when the weight is resting

on any obstruction.

The drillers' logs of material passed through in sinking wells should be obtained whenever possible. The logs of deep wells are especially valuable as evidence of the geologic structure of the region. Good judgment must be used in studying the logs of wells, as many of the logs will be found to be inaccurate. To assist in this study therefore, information should be obtained in regard to the reliability and experience of the various drillers. The method of drilling the well should also be noted. The following are the logs of two drill holes put down in the same pit, not over four feet apart. Similar well rigs were used for the two wells, and both the drillers were experienced men.

A	B
37 - 47 Coarse gravel	
47 - 49 Blue clay	45 - 54 Coarse gravel
49 - 56 Caliche	
56 - 58 Solid cement conglomerate	
58 - 62 Fine gravel	54 -104 Clay and caliche
62 - 64 Fire clay	
64 - 70 Quicksand	
70 -108 Caliche	104-108 Coarse gravel
108-112 Sand	
112-117 Caliche	108-125 Clay and caliche
117-123 Coarse sand	
123-126 Hard sand	
128-130 Coarse sand	

The caliche referred to in the above records is a calcareous substance, similar to a soft limestone, that is frequently found in the arid regions. Caliche is practically impervious to water. An inspection of the two logs will show that they

are so contradictory that it is difficult to believe that both can be correct. Other instances where pits have been dug around drilled holes have revealed many inaccuracies in the driller's log. In a few cases the driller may have knowingly falsified his log, but usually the inaccuracies are do to carelessness in keeping the original record or to the driller's lack of skill in recognizing the structure of the material passed through. Data regarding the methods used in sinking wells, difficulties encountered, and final success is valuable as a guide to future well construction.

Samples of water should be collected from representative wells for chemical analysis.

The information obtained in such a reconnaissance should be plotted so as to show the main features of the area to be studied. Geologic cross-sections of parts of the area may be drawn.

All available rainfall and runoff records should be obtained and studied to learn the mean annual precipitation and its distribution both as to seasons and as to localities. A map, showing lines of equal average rainfall should be prepared in order to estimate the average rainfall over the entire drainage basin.

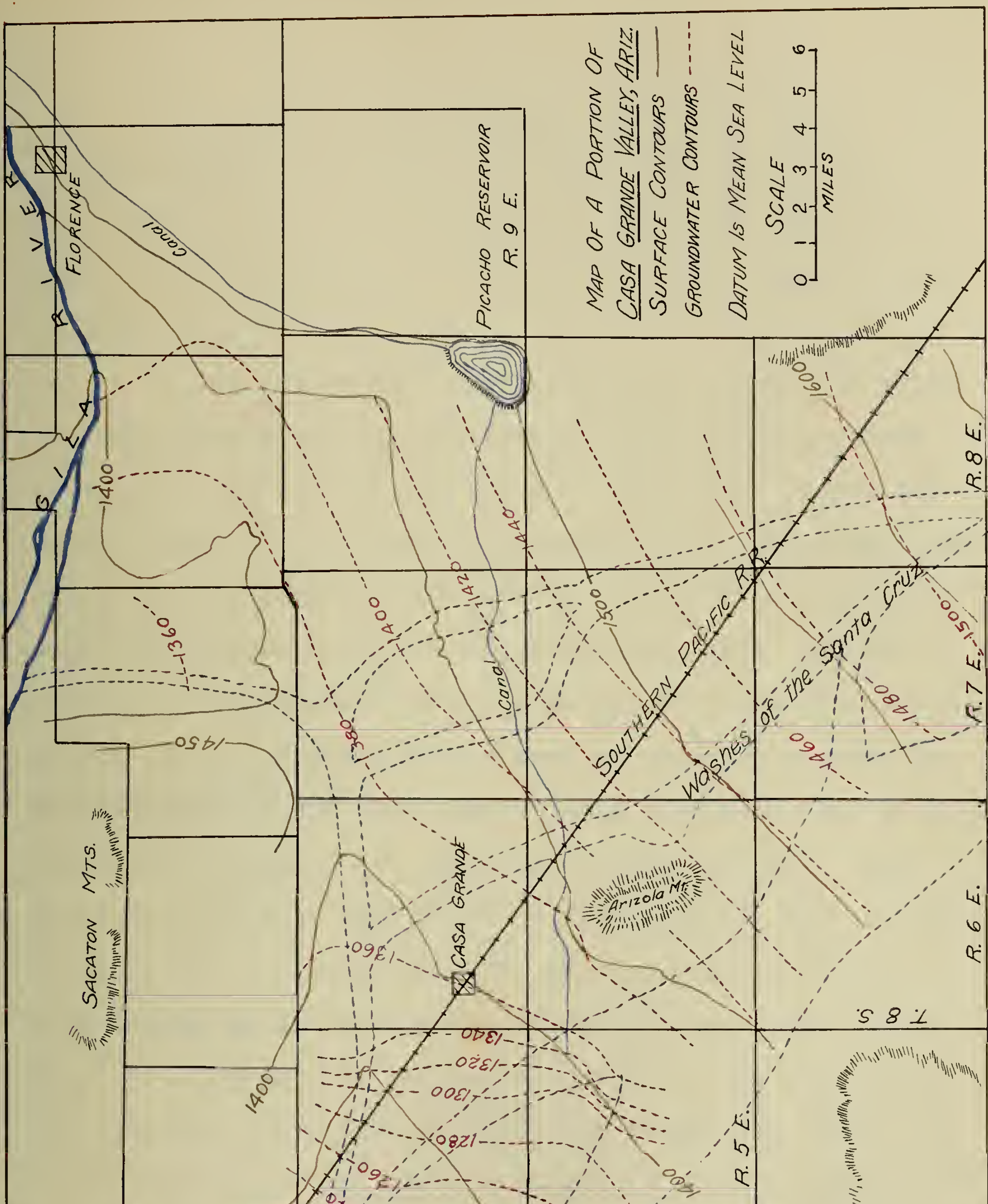
The foundation of a groundwater study is a map showing contours of the groundwater surface. Data for such a map can be obtained by leveling parties consisting of two men each, levelman and rodman. Lines of differential levels are run between the bench marks on the wells, and the

wells are tied in to land lines by rectangular coordinates. Such a party can run lines from two to seven miles long per day, depending upon the character of the country and the distance between wells. The accuracy of the leveling should correspond to the secondary leveling of the United States Geological Survey. Sufficient data can be obtained by such a party, with but little additional labor, so that surface contours may also be drawn in. The work of the level parties will be hastened if sketch maps have been previously prepared showing the wells to which levels are to be run, and their approximate or correct location. If records of the fluctuations of the water surface in the wells are to be continued for several years, reference bench marks should be established at a permanent point near each well, in order that all the measurements to water may be referred to the same datum, even if the original bench mark is destroyed by changes about the top of the well.

Lines of equal depth to water may also be drawn on the groundwater map. Often only a few such lines are drawn; such as the line of eight foot depth to water, the approximate boundary of an evaporation area; the line of twenty five foot depth to water, being the boundary of the shallow water district, and the line of one hundred foot depth to water, being the approximate limit of successful pump irrigation. It is often convenient to divide the area into several subdivisions according to the depths to water.

In Plate II. is shown a map of a portion of the Casa Grande Valley, Arizona, with both surface and groundwater contours. Over the greater portion of the area shown, the groundwater and surface contours are parallel. The main supply of ground water is seen to be from the southeast, the main underflow being parallel to the Santa Cruz Washes. The influence of the Gila River is seen to extend only a few miles south of its channel. Arizola Mountain (southeast of the town of Casa Grande) apparently has little effect on the ground water, but a buried ridge west of Arizola Mountain does influence the water table greatly, although there is no surface indication of its presence. The buried ridge acts as a dam, holding the underflow back and raising the water table to within twenty five feet of the surface. Immediately below this dam the water table drops rapidly, and the depth to water in wells is increased to over one hundred feet. Wells on the buried ridge often penetrate into rock and are generally failures. It will be seen that the Casa Grande Valley is in reality the delta fan of the Santa Cruz River. It is only upon rare occasions that floods in the Santa Cruz are large enough to reach the Gila River. Usually the floods spread out over the washes and are entirely dissipated by absorption into the soil. The lack of fluctuations of the water table indicates that the places of inflow to the ground water are situated upstream at some distance from the area shown in this map.

PLATE II


MAP OF A PORTION OF
CASA GRANDE VALLEY, ARIZ.
SURFACE CONTOURS
GROUNDWATER CONTOURS
DATUM IS MEAN SEA LEVEL
SCALE
0 1 2 3 4 5 6
MILES
GILA RIVER
FLORENCE
Canal
PICACHO RESERVOIR
R. 9 E.
R. 8 E.
R. 7 E.
R. 6 E.
R. 5 E.
R. 4 E
T. 4 S.
T. 6 S.
T. 7 S.
T. 8 S.
SOUTHERN PACIFIC R.R.
Washes of the Santa Cruz
SACATON MTS.
CASA GRANDE
Arizola Mt.
N
E
W
S
1400
1360
1450
1380
1400
1420
1440
1500
1600
1500
1480
1460
1360
1340
1320
1300
1280
1260
1240
1400
1220
1200
1180
1300
1300

In areas having artesian water, the contour lines of any hypothetical surface, to which the water in the wells would rise if free and there was no discharge, may be drawn, using the static head as measured by pressure gages on the capped wells.

The groundwater map shows the direction in which the underflow is moving, indicates the principal sources of supply, and indicates where the groundwater losses are taking place. A groundwater map made before the development of an area is begun is valuable as a basis for determining what the effects of the development have been. For this reason, in any project where there may be a question of the effect of the proposed development on existing rights, an accurate map of the groundwater table should be made before the construction of the collection works is begun. The groundwater table may be said to be an indispensible part of any groundwater investigation. The surveys may be made most accurately, as in Long Island where the surveys are to be used for planning the collection works, or the map may be constructed from depths to water and elevations taken off a contour map, or the map may show only lines of equal depth to water; but any groundwater investigation is far from complete if there is no chart showing the form of the water table.

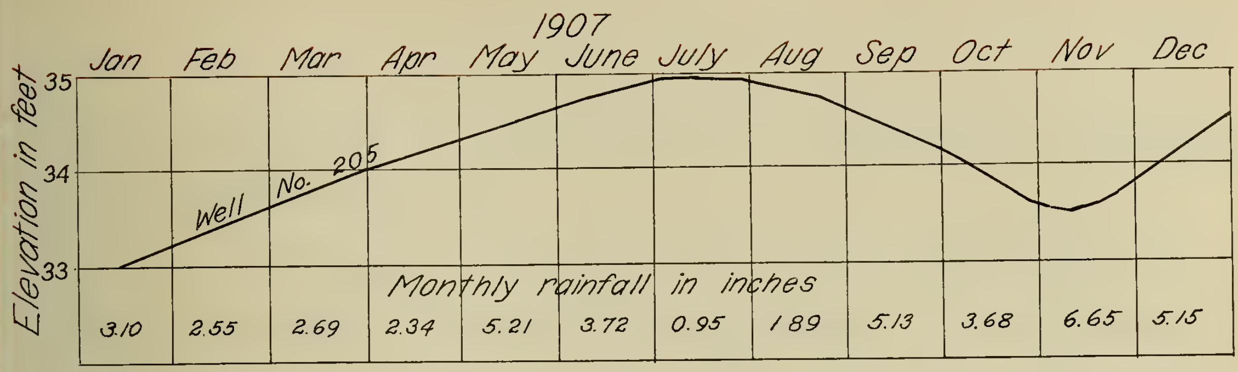
If the measurements of the depths to water in the wells are repeated at intervals, records of the groundwater fluctuations will be obtained. Where the fluctuations are

rapid, it will be necessary to take the measurements at short intervals, possibly every day during periods of great change. In other cases three or four measurements a year will be sufficient. The records, in any case, should extend over at least one year, and preferably over many years.

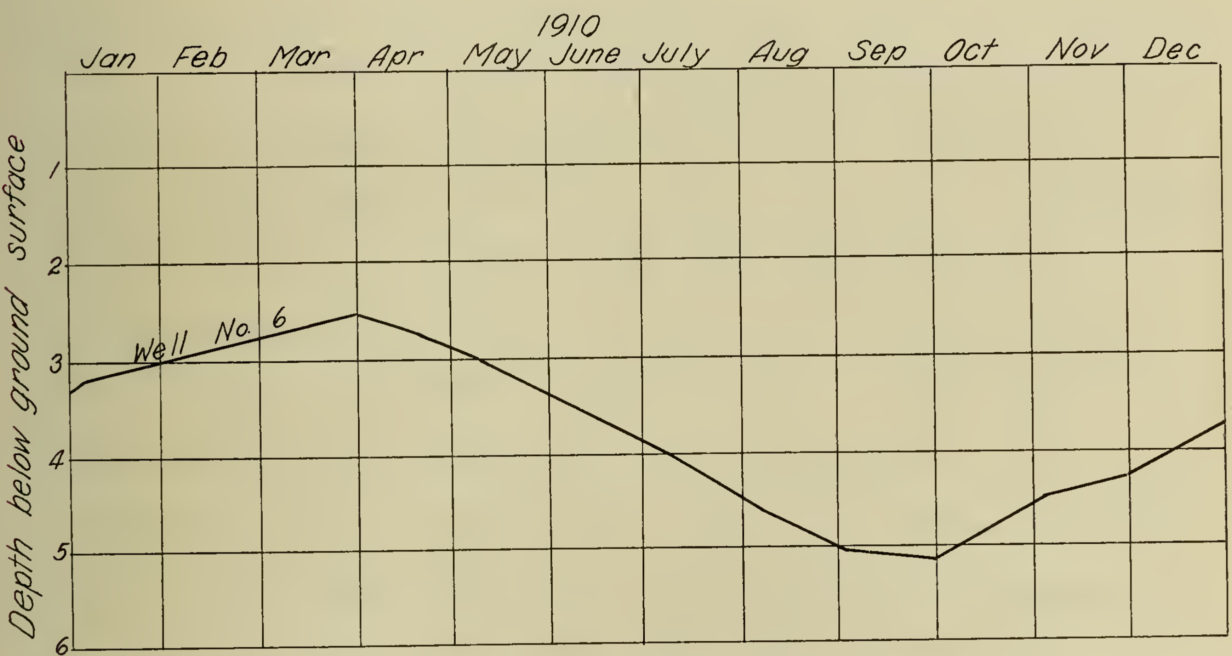
By studying the fluctuations and tracing out their causes, the sources of the groundwater supply may be located, and some idea of the magnitude of the accessions from the various sources may be obtained. In an investigation of the Niles Cone, near the south end of San Francisco Bay, estimates of the accessions to the underflow were made for several seasons, using the rise of the groundwater table during the rainy season and estimating the porosity of the saturated strata.

There are two difficulties attendant upon the use of groundwater fluctuations for quantitative measurements of the gains of the underflow; the impossibility of obtaining accurate data regarding the porosity of the material filled or emptied by the rising or falling water table, and the necessity for making estimates of the normal losses during the period of rise. For the last reason, quantitative estimates can be made only when the inflow to the ground water takes place during a comparatively brief interval, in which case the losses may either be neglected or be closely estimated. It is manifestly impossible to make estimates of the inflow to the underground reservoir from the fluctuations of the

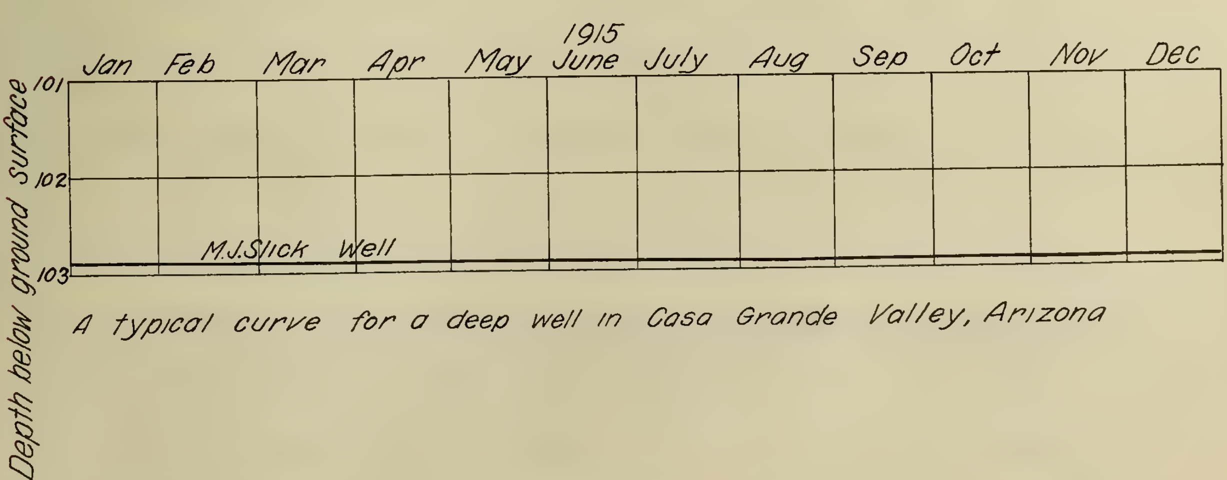
PLATE III



A typical curve for a Long Island well. Ground surface about 20 feet above water table. From "Long Island Sources" Board of Water Supply, New York City.



A typical curve for shallow well in Owens Valley, California
Transactions, American Society of Civil Engineers, Vol. LXXVIII



A typical curve for a deep well in Casa Grande Valley, Arizona

water table when inflow and outgo are taking place continuously throughout the year.

The greatest value of records of fluctuations of the water table is in checking hypotheses of how the groundwater supply is replenished, or in checking estimates of groundwater losses and gains. The hypotheses or estimates must offer a satisfactory explanation of the fluctuations or else be considered as inaccurate.

In Plate III are shown typical fluctuations for various conditions. The upper curve is the record of a well in Long Island, New York, where the annual precipitation is more than forty inches. The curve of this well is quite uniform with a crest in the spring or early summer, and a trough in the fall or early winter. The second curve shows the fluctuation of the water table in the vicinity of an evaporation area, where the inflow is fairly constant throughout the year, the fluctuations being due to varying transpiration and evaporation rates. The similarity between the first two curves indicates that the fluctuations are due to similar causes. The third graph shows the absence of fluctuations in a well that is deep to water and is distant from the areas of supply and areas of losses. Seasonal variations in supply or outgo have no effect on the water table in the vicinity of this well; even though the latter part of 1914 and the first few months of 1915 were unusually wet, followed by a drouth for the remainder of the year, thus accent-

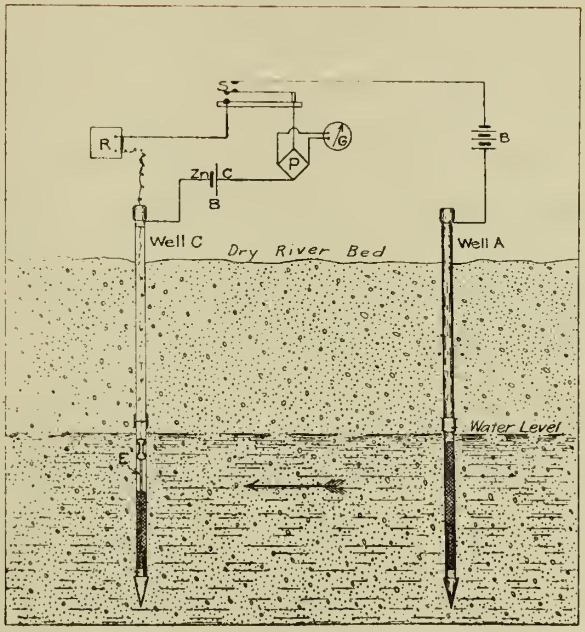
uating the effect of transpiration and evaporation, the water table remained constant the entire year.

The direct method of determining upon the quantity of underflow is to measure the area of water bearing strata in a given section, and find the average velocity of the flow through the section. The discharge will be given by the equation:

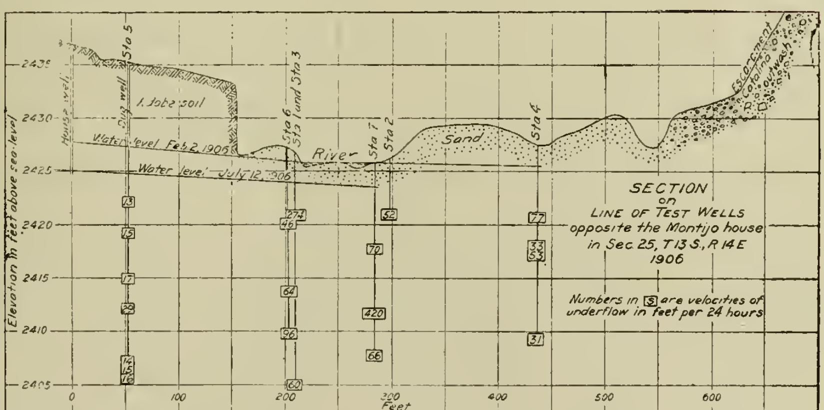
$$Q = pav$$

where Q is the discharge, p the porosity, a the area of water bearing material in the cross section, and v the velocity of flow through the section. The area of the water bearing material can be determined by making a sufficient number of borings across the section. The determination of the average porosity is much more difficult, or is even impossible, because of the difficulty of getting samples of the water bearing material in its natural state. It is often assumed that the sand or gravel is packed so as to give minimum porosity in its natural state, and therefore in testing sands and gravels for porosity it is customary to compact the materials as much as possible. There is considerable doubt as to the accuracy of this assumption.

The flow of water through sand is not comparable to the flow of surface waters, but is more like the flow of water through a bundle of various sized pipes. There is little relationship between the flow of water in one



General diagram of underflow test apparatus. R is a rheostat, B,B are batteries, P a commutator, G is a galvanometer, S a switch, E an internal electrode, A is the salt well and C a downstream well.



Cross-section of bed of Rillito River showing velocities of underflow.

From Bulletin 64, Arizona Agricultural Experiment Station.

part of the section to the flow in another part of the section, except that both flows are caused by approximately the same head. Several methods have been used for measuring the velocity, usually the velocity is found by measuring the length of time required for some substance to flow from one well to another well directly downstream. The substances commonly used are salts, dyes, and in some instances, harmless bacteria. The arrival of the substance may be determined by analysis or examination of samples taken from the downstream well at frequent intervals; or the travel of electrolytic salts from one well to the other may be observed by measuring the varying resistance to an electric current flowing between the wells. The electric method has been the most satisfactory, because the taking of samples of water from the downstream well for analysis affects the velocity of groundwater flow. On Plate IV is a sketch showing the method of connecting the wells for electric measurements. The results of an underflow measurement are also shown on the same plate. This measurement is a notable one on account of the high velocities found, far exceeding the velocities reported by other investigators.

The probably error of such measurements is quite large, and the accuracy of the data obtained ordinarily will not justify the expense of the large number of test wells required. This method is best suited to places where the underflow is confined by underground barriers to a small section, as is often the case in mountain canyons;

but area-velocity measurements are not at all practicable for areas where the underflow exists as a broad deep sheet.

German engineers consider that pumping tests furnish the most accurate means of measuring the volume of underflow. The test well is pumped steadily with a constant discharge until the circle of influence has spread out until a volume of underflow equal to the discharge of the pumps is contributing to the well. When this point is reached the circle of influence will become constant. The cone of depression is observed by means of rows of observation wells radiating from the test well. Smreker has derived the following equation for the distance to the "culmination point" or downstream point where there is a crest in the water table; the water table sloping down, both upstream towards the well and downstream away from the well from the culmination point.

$$x_0 = \frac{q}{2\pi p H v}$$

where x_0 is the distance to the culmination point, H is the thickness of the water bearing strata and q is the pump discharge. Combining the above equation with the equation;

$$Q = pav$$

$$Q = \frac{qa}{2\pi H x_0}$$

This equation states that the area of underflow, of depth H, necessary to furnish the quantity q has a width of $2\pi x_0$.

The cost of a pumping test is likely to be quite large on account of the large number of observation wells required. The expenses will be especially heavy if deep strata are to be tested. On the other hand, the results of a pumping test properly carried out should be quite accurate, and the results are more easily understood by the laymen. Often the expense of such tests may be reduced by utilizing existing installations. In Long Island a study was made of the carefully kept records of existing plants, and from these records it was possible to compute the safe yield of several areas. By comparing these areas with the areas in which development was proposed, it was possible to make estimates which are no doubt very accurate.

The measurement of the inflow and outgo from underground reservoirs has been developed in the semi-arid regions of the West. This method of making a quantitative study of the underflow is better suited for semi-arid regions than for humid regions, as the places of groundwater losses are more likely to be separated from the areas of inflow into the underground reservoir in the arid regions. When losses and gains are taking place continuously over the entire drainage area, as is commonly the case in humid regions, it is not practicable to use this method.

The main sources of supply to the ground water

are:

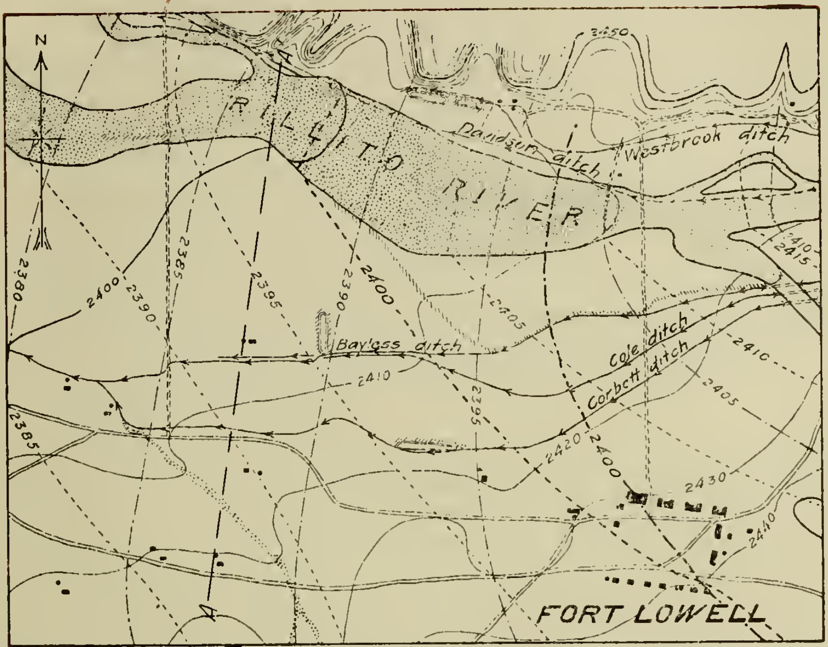
Percolation from rainfall

Seepage from streams

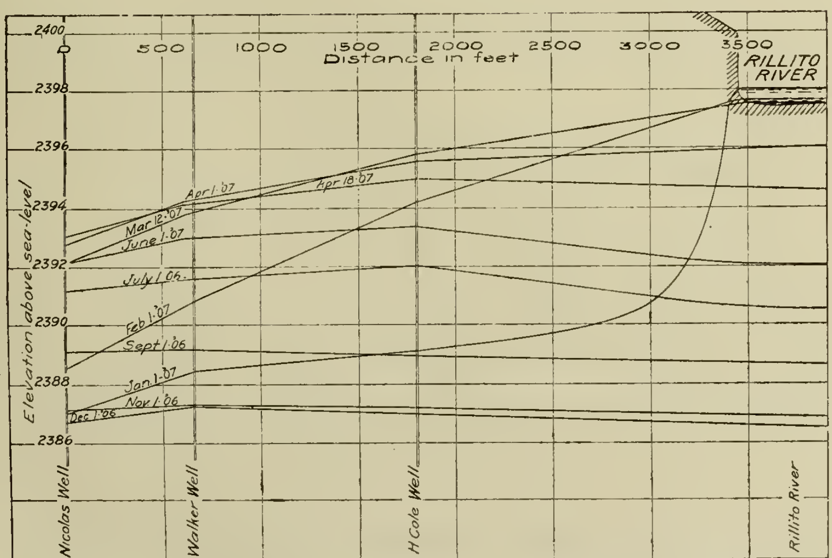
Seepage from irrigation.

In the humid regions practically the only source of supply to the groundwater is by percolation from rainfall. In the arid regions the percolation from rainfall is likely to play a minor part in the replenishing of the underflow, while seepage from floods and from irrigation systems may be the major part of the accessions to the underflow.

The direct measurement of the percolation from rainfall is only possible when a large portion of the precipitation occurs during a short season while gains or losses from other causes are slight. On the Pacific Coast, where the greater part of the annual rainfall occurs during the winter season, the percolation from rainfall can be estimated very closely from the rise in the water table during the rainy season. If the rainy season occurs during the summer, when transpiration and evaporation rates are high, the effect of the percolation will be obscured by the increased rates of water loss. Often in arid regions it will be possible to demonstrate that there is no percolation from rainfall by making borings with a soil auger. As long as there is a strata of dry soil above the water table, moisture cannot pass downward to the ground water.



Shape of the water table at the end of a dry season and after a flood season. Continuous lines are surface contours; dot and dash lines are groundwater contours of Nov. 1, 1906; and the dotted lines are water contours for Feb. 1, 1907.



Profiles along line A-A' in the above sketch map.

From Bulletin 64, Arizona Agricultural Experiment Station.

The factors controlling seepage from streams are as follows:

Character of stream bed

Temperature of the stream waters

Position of water table

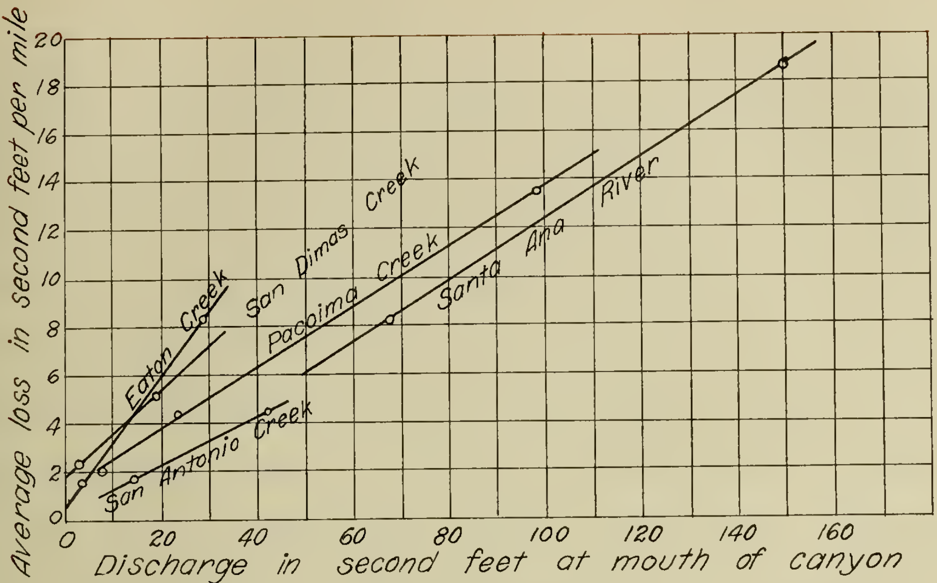
Turbidity and character of the material held in suspension in the stream

Velocity of flow

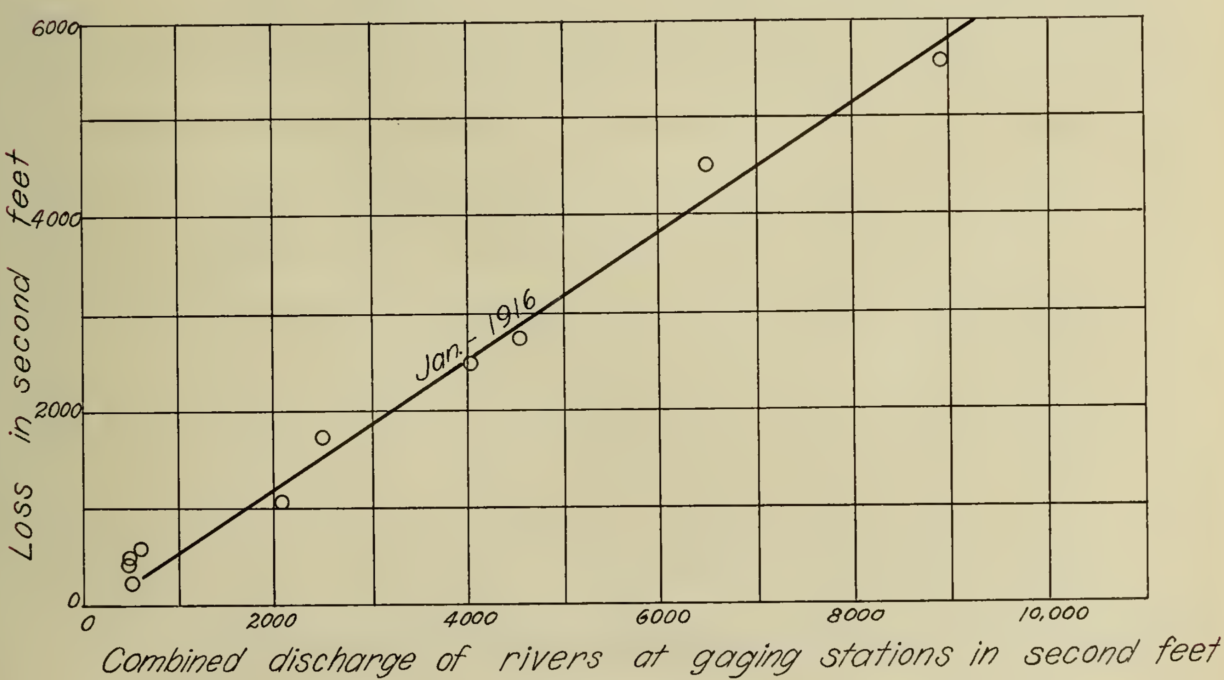
The effect of the first two factors is clearly shown by the formulae for flow of water through sands. The position of the water table affects the rate of seepage by varying the head causing the water to flow through the stream bed. If the water of the stream is turbid, especially if fine material is carried in suspension, clogging of the stream bed will prevent seepage, unless the velocity of flow is sufficient to prevent the deposition of the fine material.

Plate V. shows the effect of seepage on the water table in the vicinity of the Rillito River. This river carries water during floods only. The river bed is composed of sand, and during floods the bed of the river is constantly changing, hence there is little opportunity for clogging to take place.

In Plate VI. are curves showing the seepage losses from several California and one Arizona stream. The records of these streams indicate that the seepage losses are proportional to the quantity flowing.



Graphs showing seepage losses from several California streams. From Report of the California Conservation Commission, 1912.



Graph showing seepage losses of the Santa Cruz and Rillito Rivers between the gaging stations above their junction, and Sasco. The distance is about 33 miles. From the records of the Arizona Agricultural Experiment Station.

Although these curves indicate such a definite relationship, changes in turbidity or in the position of the water table may affect the rate of seepage very much. Therefore, when possible, gaging stations should be established at each end of the section where seepage takes place and continuous records kept of the flow at each station. However, if it is inadvisable to keep records at more than one point on a stream, occasional measurements of the seepage together with records of changes in conditions affecting seepage will allow of the making of accurate estimates.

The frequent rise of the water table following the opening up of new irrigation projects attests to the fact that a large part of the water diverted for irrigation finds its way to the groundwater. The larger part of this seepage occurs in the canals and laterals; over half of the water diverted being lost before it reaches the ranchers' headgates on many projects. Poor methods of irrigation result in more water seeping down to the water table from the irrigated fields themselves. With the modern system of charging for irrigation water according to the water delivered at the ranch, the records of the irrigation company will reveal the amount of seepage from the canal system on many projects. If sufficiently accurate records are not kept, current meter measurements can be made at various points so as to collect enough data for estimates of the canal

losses. It is not possible with present methods to measure directly the seepage from irrigated fields, but the seepage must be estimated from the water requirements of the crops grown and the amount of water applied. The probable error of such estimates is of course quite large.

Losses from the underground reservoir may take place:

By seepage into streams

By evaporation from ground surfaces

By transpiration

By seepage to the sea.

Seepage into streams or springs may be measured in the same way as seepage from streams, by the usual methods of stream measurement.

Evaporation removes water from the underflow only when the water table is relatively near the ground surface. It has been found that eight feet is about the limiting distance to which capillary forces can raise water; and it has also been found that evaporation takes place at or very near the ground surface only. The distance to which capillarity can raise water depends upon the character of the soil; the finer the soil, the higher that water may be lifted. The measurement of soil evaporation is a matter of great difficulty, because of the difficulty of duplicating natural conditions for test purposes. Lee, in Owens Valley, made an extensive

series of experiments for evaporation under the conditions found in that area. Sufficient work has not been done, however, to permit the use of his results in other areas having different soil conditions, different temperatures, and different humidities.

Transpiration, or evaporation from the leaves of plants, is a much more active agent in removing moisture from the ground water than is evaporation from the ground surface. It has been found that transpiration follows the laws of evaporation very closely, and it is to be hoped that the relationship between evaporation as determined by some standard method and transpiration will be worked out eventually. According to Cannon, the roots of resistant species of trees such as the mesquite will attain the level of perennially moist soil just above the water table, under favorable soil conditions, where the depth to the water table is less than forty feet. When the depth to water is more than sixty feet in regions of relatively little rainfall, forests of mesophytic trees are lacking. At present there is but little data available on the transpiration losses from trees, and it is difficult to make any estimate of such losses. Much experimental work has been done with regard to the transpiration of field crops, the results being generally expressed in terms of pounds of water to pounds of dry matter produced.

The valleys of the Southwest, where most of the attempts to evaluate the groundwater losses have been made, are usually closed basins having no outflow of ground water. The shape of the water table will disclose whether there is any outflow or not. If there is, an estimate of the quantity flowing may be made by use of one of the formulae for flow of water through sands. However, there are likely to be so many unknown factors that must be given assumed values, that the probable error of the result will be great. In case the losses by underflow from the valley are a large proportion of the total, it will be impossible to make close estimates of the losses.

The safe yield of a groundwater reservoir is the amount which can be drawn from the ground annually without causing a continuous lowering of the water table. The safe yield, therefore, will be equal to the accessions to the underflow less the losses which cannot be avoided. In the valleys of the arid regions which have central evaporation areas, it has been suggested by Lee that the evaporation area be used as a criterion for checking the draft on the ground water; as long as part of the evaporation area persists, the safe yield has not been exceeded. In humid regions the safe yield may be limited by the quantities which must be allowed to run in surface streams to maintain prior rights.

V. THE DEVELOPMENT OF UNDERGROUND WATERS

When water is pumped from wells the water table near the well is drawn down. The amount which the water table is lowered depends on the quantity pumped or the discharge from the well, the extent and character of the water bearing strata, and the slope of the water table. Theoretical studies into the flow of water into wells have great interest because of the desirability of being able to forecast the performance of individual wells, but, because of the many uncertainties of the problem, the formulae developed are more valuable for the general tendencies which they reveal rather than for their applicability to any particular case.

The following simple mathematical investigation of the flow into wells is taken from Turneaure & Russell's Public Water Supplies. In the upper figure of Plate VII "let it be assumed that AB, the original surface of the ground water, is horizontal and at a uniform distance H above an impervious stratum; that the porous material is uniform; and that the well is sunk to the impervious stratum. Let r = radius of well, h = depth of water in the well when in operation, H = original depth of ground water, x and y = co-ordinates of any point of the curve CF referred to the bottom of the well as origin, and Q = rate of flow into the well, or yield.

"The total available head, as represented by H-h,

is consumed in four ways: first, and mainly, by the resistance to flow in the ground; second, by the entrance resistance into the well-tube or well; third, by friction in the well-tube in ascending to DE; and fourth, by the head necessary to give the rising water its velocity. For shallow wells all but the first are usually very small, and for the present they will be neglected.

"The equation of the curve CD-EF will now be derived. The flow being radial, the area of the cross-section through which the water passes at the rate Q at any distance x from the center is that of a cylindrical surface equal to $2\pi xy$." It was previously shown that a general form of the equation for the flow of water through sand was:

$$Q = ksAp$$

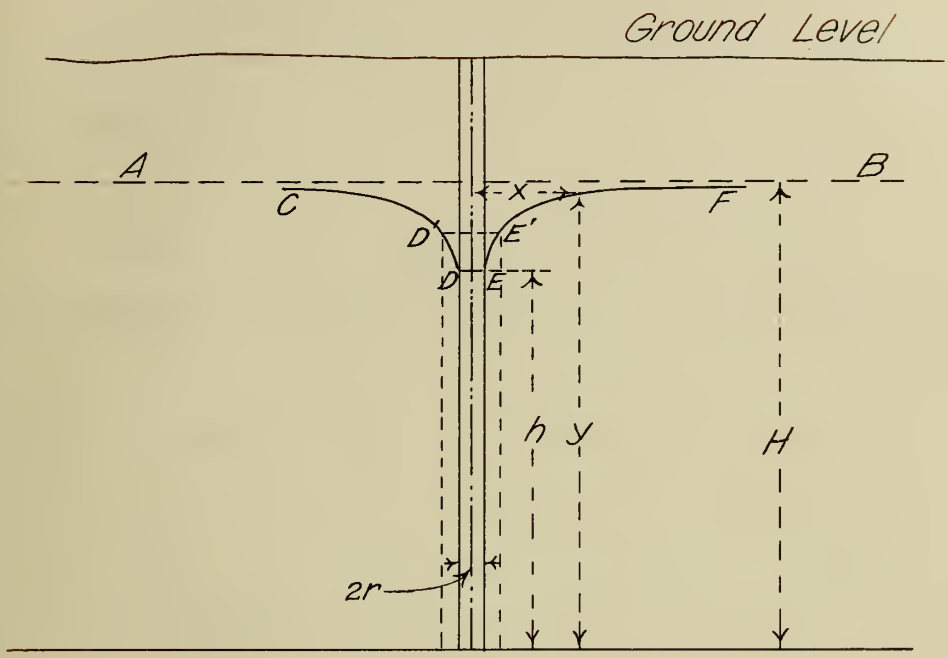
where k = a constant for the particular sand in question, s = slope, A = area of cross-section in square feet, and p = porosity. "In this case $A = 2\pi xy$ and $s = \frac{dy}{dx}$, whence

$$Q = 2\pi kpxy \frac{dy}{dx} \qquad (1)$$

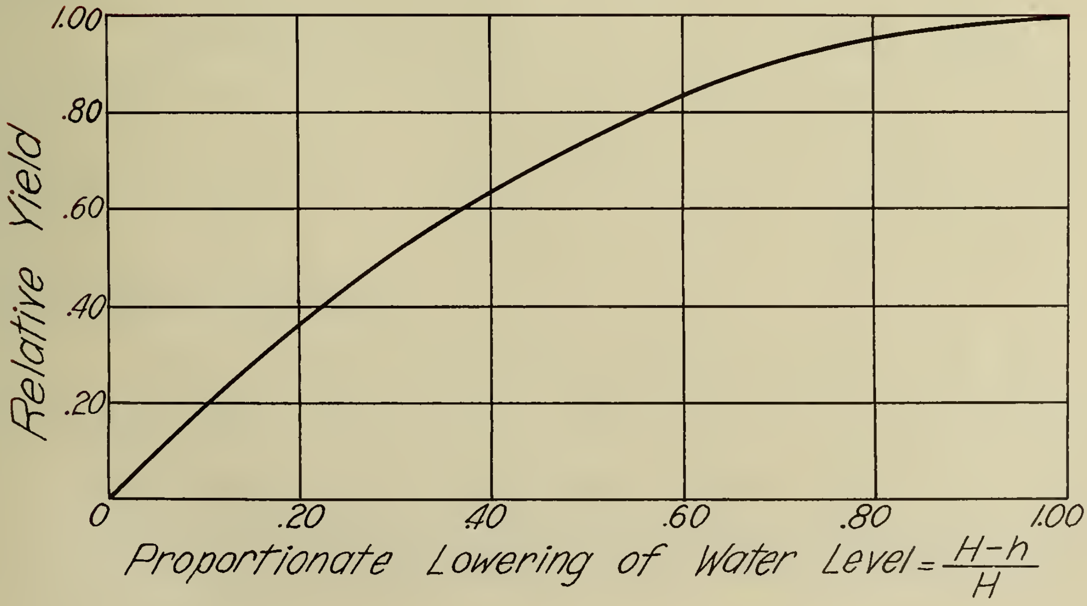
Writing this in the form $Q\frac{dx}{x} = 2\pi kpydy$, and integrating, we have

$$Q \log_e x = \pi kpy^2 + C \qquad (2)$$

in which $\log_e x$ is the natural or hyperbolic logarithm of x. When x = r, y = h, whence we find $C = Q \log_e r - \pi kph^2$, and substituting and solving for y^2 we have



SECTION THROUGH WELL



From Turneaure and Russell's "Public Water Supplies"

$$y^2 = \frac{Q}{\pi k p} \log_e \frac{x}{r} + h^2 \qquad (3)$$

which is the equation sought. The units are the foot and day."

"This formula assumes the water to flow towards the well from an indefinite distance, and the curve therefore continues to rise indefinitely, but more and more slowly as we recede from the well. In the actual case the circle of influence is limited on account of the flow of the body of ground water, this flow being maintained by percolation either near or remote. Furthermore, on account of the slope of the groundwater surface, the curve will be modified, being steeper on the up-stream and flatter on the down-stream side. It will also be more or less irregular on account of variations in the porosity of the ground."

Further modifications are made in the formula as derived above, to allow for the amount of water actually flowing in the ground. This is done by introducing a term R which is that value of x for which the change in water level is inappreciable.

The effect of lowering the water table, on the yield, is shown graphically in the second figure of Plate VII In artesian wells, where the water bearing strata are not uncovered, the discharge will be very nearly proportional to the drawdown.

It is also shown that the diameter of the well has but little effect on the discharge for a given draw-

Maximum Quantity of Water in Gallons per Minute That It Is Practicable to Pump with Various Deep Well Pumps

Type of Pump	Inside Diameter of Well Casing – Inches									
	3	4	5	6	7	8	10	12	14	16
Plunger Pumps										
Single Acting	10	18	36	54	75	100	140			
Double Acting	12	28	48	85	125	170	300	430		
Turbine Pumps							500	900	1200	1500
Propellor Pumps				250	450	900	1400	2500		
Air Lift	25	100	250	350		650	1000			

down, hence from theoretical reasons, small wells are the more economical. However, in practice, the needs of pumping machinery make larger wells necessary. In Plate VIII is a table showing the maximum quantities which can be pumped from drilled wells of various size by different kinds of pumps, based on the claims of manufacturers. Large wells are also preferable to small wells because they provide more screen area. In Arizona drilled wells for pump irrigation are seldom smaller than twelve inches in diameter, sixteen inches being a common size. The general tendency in well drilling for the past few years has been toward larger wells.

In spite of the fact that the water table in almost all cases is sloped in such a way as to indicate a definite underflow; in actual practice, with shallow groundwaters particularly, there is often not a definite, growing underflow, comparable with a surface stream, but, instead gains and losses are taking place throughout the entire course of the flow. For this reason, large developments of the underflow often affect downstream projects much less than had been anticipated. In fact, the influence of a well ordinarily extends about as far upstream as downstream. More water can be obtained from a system of wells uniformly spaced over the whole district than can be obtained from a row of wells at right angles to the underflow. The yield of a row of wells that are

pumped continuously at their full capacity, quickly reaches a point where it is limited by the quantity of underflow. Wells spaced uniformly over the area, on the other hand, can draw upon the storage of the underground reservoir to a much greater extent; and, if there are periods when the recharge to the groundwater supply is limited only by the available capacity of the underground reservoir, a much larger quantity of ground water may be withdrawn. For irrigation in the arid valleys of the Southwest it has been found economical to sink a well at the high point of each farm or group of farms than to attempt to secure a large supply in one spot. In the Santa Cruz Valley near Tucson, Arizona, which has been developed by many small pumping plants, yielding from one to five second-feet each, the water table fell steadily for four or five years preceding the fall of 1914. The winter season of 1914-15 was a period of unusual rains and floods, with the result that the water table over the entire valley was quickly restored to its original level. The shape of the water table indicates an underflow continuing the length of the valley, but the records of the fluctuations of wells shows that the inflow to the underground reservoir takes place simultaneously throughout the entire area. If the underflow receives no accessions except from a distant, upstream source (as is the case with artesian waters) a row of wells at right angles to the underflow will furnish as much water,

as wells located according to any other arrangement, because the yield of the wells will be limited by the underflow, except for very short periods. For municipal supply it is convenient to bring the entire supply to a central pumping station, and for this reason, wells for such a supply are generally arranged in rows in order to reduce the amount of piping for connecting the wells. Ordinarily an attempt is made to place the row of wells at right angles to the underflow, although, as stated by Smreker, a similar row of wells parallel to the direction of underflow will yield an equal amount of water with the same drawdown. The water level will be nearly the same in all the wells of a row perpendicular to the underflow, and this is sometimes an advantage in favor of that arrangment. The wells should be placed as far apart as conditions will permit (up to a distance of half a mile or a mile in water bearing strata similar to those found in most Arizona valleys). Sometimes a group of wells is sunk, generally three, in a row about fifty feet apart, and all the wells are pumped by a single pump. Apparently the chief advantage of such an arrangment is the increased strainer area afforded.

The oldest method of constructing wells is to dig a pit into the water. There is little difficulty in digging the pit to the water level, but it is very difficult to extend the well below water. In humid climates the well must be curbed from the surface of the ground to the bottom.

In the arid regions wells stand for years with only a collar at the top to keep surface water from running in, and with short sections of curbing opposite any sand strata passed through. However, it is advisable to curb the well the entire depth even in arid regions. The well must have some kind of a curb below water unless in rock, because saturated soils will not stand. The well may be timbered according to ordinary shaft sinking methods, or the curb may be sunk as a caisson. Caissons may be built of cast iron, brick, stone masonry or re-inforced concrete. The excavation may be made by dredging with orange-peel or clam-shell buckets, or the material may be dug out by manual labor, the water level being kept low in the pit by pumping. A man can dig in ankle deep water with little loss in efficiency. Water at knee depth slows a man down, part of each shovelfull will be washed off while the shovel is being brought up through the water, and it will be necessary to substitute a bar for the pick in hard strata. When a man is waist deep in water he will be able to dig very slowly. For economical excavation, therefore, water should be kept down so as not to be over a foot in depth. In order to keep the water down, it is necessary to lower the pump as the excavation progresses; or add to the pump suction; or install the pump suction in a drilled hole previously made. The first method is most easily used with direct connected pumps, or when pumps similar to the pulsometer steam

pumps are used. With belt driven pumps it is more difficult to lower the pumps. The second method or a combination of the first and second methods is commonly used. One or two-foot lengths of suction pipe are attached as the excavation is carried downward. A small sump is excavated ahead, around the suction pipe so as to keep the water low in the remainder of the pit. However, just before a length of suction pipe is added the water in the pit will necessarily be rather deep. Suction hose, though apparently ideal for this kind of work, has not proven a success, it being difficult to keep the connections tight. With a pump installed in a drilled well around which the caisson is to be sunk, there will be but little difficulty in lowering the pit to the depth of the draw-down of the pump. The expense of drilling the pioneer well offsets to a certain extent the advantage of this method, but where a drilled well already exists, the cost of excavating a pit below the normal water level can be materially reduced by digging the pit around the drilled well. Centrifugal pumps are well adapted for pumping from the excavation, because of the absence of valves to be clogged and worn by sand. It is also easier to vary the discharge of centrifugal pumps (either by changing the speed or by throttling the discharge) than with other types of pumps. Because of the temporary character of timbering when alternately exposed to water and air, as

in wells; and because of the difficulty of replacing decayed timber below the normal water level; it is seldom justifiable to use wood for casing the well below water. Because of the great expense of excavation below water the extra cost of a permanent lining will not add greatly to the cost of the well. With the more permanent forms of curbing, the curbing below water is usually sunk as an open caisson. Concrete has been used more than other materials for open caissons, because of its many advantages. Cement is fairly cheap, and the concrete curbs can be built of the desired shape by ordinary labor. It has been found desirable to have a metal shoe to protect the cutting edge of a concrete caisson, and usually the caisson is reinforced to withstand the shocks of sinking. The thickness of the walls of the caisson is dictated more by the need of weight to overcome skin friction during sinking than for strength. The experience of the Arizona Agricultural Experiment Station has indicated that the inside diameter should be from six to eight feet, depending upon the size of pump that will be required. The United States Reclamation Service has found an inside diameter of nine feet to be sufficient for wells yielding 4500 gallons per minute. It is customary to excavate a pit to water level and then build the caisson in the pit. Sometimes the entire caisson is constructed before sinking is begun, in other cases

sinking is begun as soon as a part of the caisson is complete and has thoroughly set, the remainder of the caisson being added as the caisson settles down. The caisson should be largest at the bottom, the outside growing smaller from the bottom up, so that the caisson will have a tendency to free itself from the surrounding material as it drops downward. After sinking has once been begun, the work should be prosecuted vigorously until the caisson has been lowered to its final position. If the work of sinking the caisson is interrupted for a time, the surrounding material will pack around the caisson and the skin friction will be greatly increased. To overcome skin friction it is necessary at times to load the caisson with weights. A refractory caisson can sometimes be induced to drop downward by moving it slightly with jacks acting horizontally against its top. Pouring water around the outside of the caisson will decrease skin friction temporarily, but it also has a tendency to pack the soil more closely around the outside of the caisson, thereby increasing the skin friction. Great care should be used to keep the caisson plumb, especially during the first part of sinking, as it is very difficult to straighten a caisson that once begins to tilt. In hard strata, the caisson, instead of lowering gradually, will move downward by short drops. These drops should be for short distances only for if the caisson drops far enough to gain much momentum there is danger of its being wedged into the hard material before

it stops, making it difficult, if not impossible, to induce the caisson to move further downward. When quicksand is encountered, unless the curb has great weight, there will be a flow of the fluid material under the shoe and into the excavation. A much greater volume of sand will have to be hoisted out of the pit than is occupied by the caisson. Cavities will be left outside of the caisson which may cause overlying strata to cave (even above the normal water level) and the final result may be that skin friction is increased by the packing of the falling material against the outside of the caisson. In case the caisson is to be sunk through a water bearing stratum into an impervious one, holes should be provided in the wall to allow the water from the pervious stratum to enter the well. In case only one stratum is being developed, and the water table is to be drawn down nearly to the shoe of the caisson during pumping, the seep holes are not so necessary as the bulk of the flow of water will be under the shoe and up through the bottom of the well. However, seep holes should be provided for in building caissons, as it is expensive to drill holes in the hardened concrete should it be found desirable later to have openings in the wall.

Where the water table varies from season to season, a caisson should be put down at the time of lowest water; otherwise the yield of the well may not be sufficient during the season of low water table.

The advantages of large wells constructed as above described are as follows:

1. The water bearing strata passed through can be permanently developed.

2. The well is thoroughly tested by the pump used to keep the water down during the excavation of the well, and it is possible to design a pumping plant for such a well with no doubt as to the future operating conditions.

3. The large pit allows greater latitude in the selection of pumping machinery.

4. Concrete or cast iron curbs will have a long life.

The disadvantages of large wells are as follows:

1. High cost. The cost increases rapidly with increasing depth below the water table, and with greater depths below the ground surface. The high cost makes the development of deep strata impracticable.

2. A much longer time is required for the construction of wells such as described than for drilled wells.

Of the many methods of sinking wells of small diameter, there are only three in general use in Arizona; boring with earth augers, drilling with drop drilling rigs, and drilling by the hydraulic rotary process.

Boring with augers is a rather crude method of well sinking. The apparatus used is generally home-made

and all of the work of drilling is done by man-power. The drilling outfit consists of an auger bit, rods, and derrick or tripod with a windlass for hoisting the tools. The bit is similar to the bit of a post-hole auger. The rods are lengths of pipe, squared at one end and with a square socket at the other end which will slip over the square end of the adjoining rod. The rods are held together by pins passing through the square socket and the square end of the rods, the pins being held in place by cotter pins or baling wire. The rods and auger are turned by means of a cross-bar that is fastened by a pin to the upper joint of drill rods. Holes are drilled through this upper joint of pipe at frequent intervals, and as the auger is worked down, the cross bar is moved up along the rod. The turning is done by two men who grasp the cross bar and walk around the well. When the barrel of the auger is full the tools are hoisted, a joint at a time, and after the auger barrel has been emptied, the tools are lowered again into the well. When the well is deep much time is consumed in hoisting and lowering the rods. The casing is generally set after the boring is completed. Strata that are firm enough to stand without casing, and which are not too hard (such as loam, sandy clay, clay, etc.) are rapidly penetrated. Boulders and coarse gravel are penetrated with difficulty.

Sand in its natural state will run out of the auger barrel while being hoisted, and even if the sand can be hoisted out, the walls of the hole through the sand stratum will not stand without casing. To overcome this difficulty a mixture of clay and water is thrown into the hole, which, with the sand, makes a sand-clay mixture that can be easily handled. When hard strata are encountered, blasting is resorted to. If thick, rock strata are encountered the well may have to be abandoned. The speed of boring depends upon the character of the strata penetrated and the freedom from accidents which delay the work. Instances have been reported where an eight inch well was completed to a depth of over a hundred feet in two days. The average progress is from five to fifteen feet per day in fairly favorable materials.

Percussion-drilling or churn-drilling is the standard method of drilling in almost all parts of the country. The apparatus used varies greatly, from the "standard" rigs of the oil fields to the small portable rigs used for test holes. The common feature of the various rigs is that there is a "string" of tools, consisting of stem, jars, and cutting tool, fastened either to a rope, cable, or line of poles, which is alternately lifted and dropped; that is, churned up and down. The stem is a solid shaft of steel whose purpose is to serve as a hammer when either "jarring

up" or "jarring down". The jars are a pair of links, by means of which it is possible to use the weight of the stem in striking a blow either upward or downward. In drilling the principal use of the jars is in loosening tools which have become fast. The well rigs commonly used in Arizona are of the portable type ordinarily known as a "California" or "mud-scow" rig. The distinguishing features of this type of rig are; the use of a heavy sand bucket or "mud-scow" for drilling, in place of the standard drilling bit, and the use of hydraulic jacks to force the casing down. The use of the sand bucket as a drilling tool makes for quicker progress in unconsolidated deposits, and most of the rigs have a standard bit for penetrating any rock strata which might be encountered. The use of the hydraulic jacks for forcing the casing down compels the use of short length casing, but there is much more likelihood of being able to force the casing down with the steady pressure of the jacks than by driving with the jars alone. A sixteen inch well drilled by a "mud-scow" rig for the University of Arizona was put down a distance of two hundred feet below water, mainly through cemented materials, at an average rate of about twenty feet per day. This may be considered as representative of what such a rig should do, when there are no accidents delaying the work.

The hydraulic rotary method of well drilling is of recent introduction but is increasing rapidly in popularity. The essentials of the rotary process are; a hollow drill pipe having a fish-tail or diamond bit at its lower end, means for rotating the drill pipe, means for pumping water down through the drill pipe and out through orifices in the shank of the cutting bit, and apparatus for hoisting the tools. Drilling is carried on by rotating the drill pipe and bit while the water pumped down through the drill pipe washes the cuttings up to the surface as it rises in the well on the outside of the drill pipe. The drill pipe is usually a four or six inch wrought iron pipe. The rotary machine is arranged to grip the drill rod so as to rotate it. The drill rods are turned at a rate of from thirty to one hundred revolutions per minute, depending upon the size of the well and the nature of the formation being cut. The pumps are designed to furnish a supply of from two hundred to four hundred gallons per minute. In passing through sand strata mud is mixed with the water that is to be pumped into the drill hole. The muddy water seals up the pores of the sand around the drill hole, preventing the loss of the circulating water, and also the walls of the hole are made firm so that there will be no caving even after the lapse of a considerable length of time. By observing the material carried up by the circulating water the driller can

obtain an accurate log of the well. When water-bearing strata are penetrated the circulating water will be rapidly absorbed into the strata. This gives the operator an opportunity to make good estimates of the amount of water that will be yielded by the various strata passed through; the more circulating water that a stratum, which is below the normal water level, will absorb, presumably the more it will yield when the well is pumped. The circulating water is led away from the well in a ditch by a roundabout way to a pool from whence the pumps force it again into the well. It is necessary to have a plentiful supply of water for this method of drilling, and where no other water supply is available it is necessary to put down a supply well with a small drop drill rig near the point it is proposed to bore the big well. A derrick is built over the site of the proposed well for the purpose of handling the tools, and usually the derrick is left over the well as part of the permanent installation. In the oil fields the derricks are sometimes over a hundred feet high, but for water wells the derricks are usually about forty feet high and about sixteen feet square at the base. Steam power is used for the hoists, for turning the rotary machine, and for pumping the circulating water. Wells up to thirty inches in diameter can be bored by this method, the size that

any given outfit can bore being limited by the size of the largest drilling tool that can be lowered through the rotary machine. The hole can be drilled full size from the beginning, or a small hole (eight inches or more in diameter) can be put down first to be later reamed out to the desired size. There is some difference of opinion as to which method is preferable. It is claimed that records of from two hundred to three hundred feet per day are frequently made in favorable materials. Special bits are used for boring rock, having revolving cutters. The casing is not put in the well until drilling is completed, hence the casing can be perforated to conform with the strata found in the well before being lowered into place. After the casing is placed it is necessary to develop the well vigorously to clear the water-bearing strata of the fine mud forced into them during drilling. For deep wells, such as are drilled in the oil fields, the rotary process is much cheaper than the churn-drilling method, and the rotary process has to a large extent supplanted the old "standard" method of drilling. For the comparatively shallow wells used for water supply the added expense of the derrick and the supply well offsets to some degree the other advantages of the rotary process.

The requirements of well casing are that it be strong enough to withstand the stresses of being placed, be strong enough to withstand earth pressures after it is in place, have sufficient thickness to permit of ordinary corrosion or else be made of non-corrosive material, and if it is desired to case off certain water-bearing strata the casing must be waterproof. Standard pipe and "well-casing" (lighter in weight than standard pipe) which come in twenty foot lengths, are much used. In New Mexico the statutes require the use of standard pipe for the casing of artesian wells. The lengths of pipe are joined together either by ordinary pipe couplings or by special drive couplings that allow the ends of the pipe to butt together. "Well-casing" is generally designated by its outside diameter. Several kinds of short length casing have been developed for use with hydraulic jacks in the "California" method of drilling; the principal kinds being the double stovepipe casing, and single collar casing. These types of casing come in two-foot lengths and are made by rolling sheets of steel into tubes and riveting them. With stovepipe casing the tubes are of two sizes, one size just fitting inside the other, and when in place, the sections are fitted together so that the joints of the inside tubes come just halfway between the joints of the outside tubes.

The single collar casing is similar to the stovepipe casing except that a six inch collar is substituted for the outer section of the stovepipe casing. The advantages of the short length casing are cheapness and that they allow of hydraulic jacks being used to force the casing down. The double casing must be perforated after it is in place in the well, while the single casing should be perforated before being put in the well. Riveted steel casings, made of perforated sheets rolled into tubes, are generally used when the well is cased after the drilling is completed, as with the hydraulic rotary process.

The functions of a well screen are to allow water to flow into the well with little loss of head, but to keep the surrounding material out of the well, to withstand the pressures of the surrounding earth, and to resist corrosion. Attempts to solve the problem of satisfying the demands of these various functions economically have brought forth many types of well screen, each of which is especially suited for certain conditions. The desirable features of a screen are: openings as large as the surrounding material will permit, and as large a ratio of area of openings to the total area of screen as is consistent with strength; the openings should be larger on the inside than on the outside so that they will not clog easily; it is probably desirable that the screen be made of one kind of

metal only, in order to reduce the tendency to electrolysis in corrosive waters; and the screen should be low in cost.

Many ingenious forms of screens have been patented that are said to be non-clogging, that offer little resistance to water flowing into the well, that will resist corrosion; but most of the patent screens are expensive, particularly in the larger sizes. In Arizona, the common types of screen are perforated sheets of galvanized steel, rolled into tubes and riveted; and casings of the stovepipe type which are perforated after being placed in the well. The first type of screen has the merit of being inexpensive but the sheets are sometimes of such light weight and the ratio of perforations to total area is often very large, so that the screens lack strength. Screens of this type (and most of the patent screens also) are usually set in place after the well is completed, making them especially adapted for the hydraulic rotary process of drilling. The method of making a screen by slotting the casing after drilling is completed has been developed principally as a part of the "California" method of drilling. There are a great variety of perforators made, nearly every driller using his own design. The two principal forms are the knife and the rolling-star perforators. The knife perforator is arranged so that the knife can be forced through the casing at any desired place and a slit made by driving the perforator with the jars for a short

distance. The rolling-star perforator has circular, star-shaped cutters, the number varying from one to four. The perforator, with the jars and stem attached, is lowered to the top of the section of casing which is to be perforated, and then by a sudden jerk a catch is released which allows the knives to spring out. Driving down with the jars on the perforator forces the knives through the casing, and as the jarring is continued the perforator moves downward, each cutter making a row of holes. Hoisting the perforator automatically pulls the knives in. As much as possible, perforating is begun at the bottom of the well and the lower strata are perforated first to avoid danger of sand running in through the perforations and burying the tools. One objection to the rolling-star perforator is that it is necessary to work downwards with it. With perforators of the knife form there is some danger of making the cuts too long, cutting a length of casing, and causing the casing to collapse. If one of the rolling knives of the star perforator should become wedged fast a similar accident might occur. Perhaps the main objections to perforating the casing are due to the fact that the work is done out of sight, where it cannot be checked up. The perforations may be too long, causing the well to collapse, or the casing may not be perforated at all.

The latter is by far the more common cause of well failures.

The purpose of well development is to make a natural gravel filter around the well screen by drawing all the fine material into the well and then either pumping the fine material to the surface or baling it out with sand-pumps. Obviously, little can be done to improve a well sunk in fine sand of uniform size, by drawing in any quantity of the sand, as the material drawn in the well is replaced by sand of the same size. Sand will continue coming into the well with the result that there will be a continued caving of the ground about the well which may extend to the ground surface. But in material containing both large and small particles (typical of most arid region sands and gravels) the removal of the finer sands from about the well produces the same effect as increasing the diameter of the well but at much less expense. The principal means of well development are by churning up and down with a sand bucket; by heavy pumping with a centrifugal or propellor pump, or with the air-lift; or by "rawhiding" the well, that is, suddenly stopping and starting a pump in which there are no valves to prevent the water from rushing back into the well when the pump stops. Because of the success of oil well operators in increasing the yield of oil wells by blasting in the bottom, it is often suggested that the

same method be used for wells for water supply. In general, however, blasting has not been a success for increasing the yields of water. In sand strata the firing of a charge in the well has a tendency to pack the strata, and instead of increasing the yield may decrease it. In rock, however, the firing of charge of explosive may open up cracks that will tap additional water-bearing seams and thus materially increase the yield of the well.

It is becoming more and more customary for the driller to both develop the well and test it before taking his rig away from the job. This is a very desirable practice, for the following reasons: the pumping test reveals whether or not the well has been properly completed; the test, if properly made, gives the owner the data needed for the successful design of a pumping plant; the driller has the hoisting equipment for setting the test pump; and the driller can remove sand brought into the well during the first pumping.

Oftentimes, especially in mountain canyons, the underflow under a dry wash will be restricted to a small area by the presence of an impervious dike at shallow depths below the stream bed. The surface indication of such a condition will be a perennial spring that rises out of the gravel a short distance

above the dike, flows for a short distance on the surface and then sinks again into the porous channel bed. Such a place will be an ideal location for an underflow dam, or waterproof wall to bed rock that will compel the underflow to rise to the inlet of a pipe line. Many such dams have been built in the arid regions, but in almost all cases the discharges obtained have been disappointingly small. The cost of the dam and the pipe line (which is generally of considerable length) makes the fixed charges so great that the supply obtained is not as cheap as pumped water.

An infiltration gallery, as defined by Spear "is simply a large well, placed horizontally in the ground below the surface of saturation, to collect and transport the ground water to a central pumping-station." Infiltration galleries have rarely been used for irrigation supplies, but have often been used for municipal supplies both in Europe and America. As with underflow dams, there is a tendency to overestimate the yield that will be obtained. An infiltration gallery built for the Tucson Farms Company was planned for a yield of forty second-feet, but the maximum flow obtained was less than twenty second-feet. Because of the high fixed charges, very few infiltration galleries are now being constructed, it being cheaper to construct and operate well-systems.

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